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Thermodynamic analysis of a novel hybrid wind-solar-compressed air energy storage system

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ABSTRACT

Wind and solar power have embraced a strong development in recent years due to the energy crisis in China. However, owing to their nature of fluctuation and intermittency, some power grid management problems can be caused. Therefore a novel hybrid wind-solar-compressed air energy storage (WS-CAES) system was proposed to solve the problems. The WS-CAES system can store unstable wind and solar power for a stable output of electric energy and hot water. Also, combined with organic Rankin cycle (ORC), the cascade utilization of energy with different qualities was achieved in the WS-CAES system. Aiming to obtain the optimum performance, the analysis of energy, exergy and parametric sensitivity were all conducted for this system. Furthermore, exergy destruction ratio of each component in the WS-CAES system was presented. The results show that the electric energy storage efficiency, round trip efficiency and exergy efficiency can reach 87.7%, 61.2% and 65.4%, respectively. Meanwhile, the parameters analysis demonstrates that the increase of ambient temperature has a negative effect on the system performance, while the increase of turbine inlet temperature has a positive effect. However, when the air turbine inlet pressure varies, there is a tradeoff between the system performance and the energy storage density.

1. Introduction

With the increasing depletion of traditional energy and growing global warming problem, the consumption of fossil fuels like petroleum, coal and nature gas increased by just 1.0% in 2015. In contrast, renewable energy consumption strongly grew by 15.2% and accounted for 6.7% of global power generation. The generating capacities of wind power and solar power had reached 435 GW (3% of global power generation) and 231 GW (1.1% of global power generation) by the end of 2015, respectively [1]. Actually, more attention will be paid to the development of wind and solar power in the future.

However, due to the nature of great uncertainty, randomness and intermittency induced by weather, location or air flow variations, the utilization of renewable energy is unstable [2,3]. It will bring a huge impact to the power grid management, operation mode, reliability, power quality and operation costs. Thus there are many methods researched to solve these problems, among which energy storage system (ESS) is recognized as the fundamental solution to bring large-scale renewable energy to the power grid [4]. Currently, available ESS can be classified as (1) electromagnetic energy storage, e.g. superconducting magnetic energy storage and supercapacitors energy storage; (2) mechanical energy storage, e.g. pumped hydro energy storage, compressed air energy storage (CAES) and flywheel energy storage; (3) chemical energy storage, e.g. battery energy storage; (4) thermal energy storage, e.g. molten salt energy storage [5,6]. For large scale electric energy storage, CAES is considered one of the most promising methods. It has the advantages of long lifetime, low costs, high efficiency and environmental friendliness [7–9].

The CAES technology employs intermittent renewable energy or off-peak electric energy to produce compressed air and then releases it to drive turbo-generator set for generation when needed. A great number of CAES concepts exist at different levels of development with respective strengths and weaknesses. Generally, CAES technologies are categorized into diabatic, adiabatic and isothermal concepts [10]. Taking into account of practicality, only diabatic CAES (D-CAES) and adiabatic CAES (A-CAES) have been studied intensively.

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Nomenclature

Abbreviations

A-CAES	adiabatic CAES
ASC	air storage cavern
ATB	air turbine
CAES	compressed air energy storage
COT	cold oil tank
CP	compressor
CWT	cold water tank
D-CAES	diabatic CAES
EPV	energy per volume
ESE	electric energy storage efficiency
ESS	energy storage system
HOT	hot oil tank
HR	heat regenerator
HWT	hot water tank
IC	intercooler
IH	interheater
ORC	organic Rankin cycle
RC	R123 condenser
RE	R123 evaporator
RP	R123 pump
RTB	R123 turbine
RTE	round trip efficiency
STC	solar thermal collector
TV	throttle valve
WH	water heater
WS-CAES	wind-solar-CAES
η_{ex}	exergy efficiency

Symbols

Ex	exergy (kW)
ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
I	exergy destruction (kWh)
i, j	sequence number
m	mass flow (kg/s)
P	pressure (bar)
Q	heat (kWh)
s	specific entropy (kJ/kg k)
T	temperature (°C)
t	time (h)
W	power (kWh)

Subscripts

0	ambient condition
A	air
in	inlet
O	thermal oil
out	outlet
R	R123
s	isentropic
W	water

Greek letters

η	efficiency
λ	isentropic exponent
π	pressure ratio

So far, there have been two D-CAES plants in the world namely the 290 MW plant in Huntorf, Germany, 1978, and the 110 MW plant in McIntosh, Alabama, USA, 1991 [11,12]. They both need natural gas consumption when compressed air expands in turbine. To utilize both the compression heat during energy storage process and the exhaust heat during energy release process of conventional D-CAES system, Zhao and Wang [13] proposed a hybrid energy system based on D-CAES system and CO_2 transcritical power cycle with liquid natural gas cold energy utilization. The net energy output and energy storage density were increased. Meanwhile, they had conducted a thermodynamic analysis of an integrated energy system consisting of a D-CAES system and a Kalina cycle system 6 [14]. Briola [15] developed a detailed mathematical model with a generic sequence of processes for a D-CAES system with underground storage site. Safaei [16] evaluated the possibility of enhancing the economic and environmental performance of a D-CAES system through recovery of compression heat for municipal heating applications. Yao [17] designed a novel combined cooling, heating and power system based on a small-scale D-CAES system. Also, the sensitivity analysis was carried out. Bosio [18] considered a promising system composed of a D-CAES system coupled with a wind farm and a hybrid power plant. Cost analysis was performed using a thermoeconomic approach. Recently, Mohammadi [19] studied an integrated ESS constituted by a D-CAES system, an organic Rankine cycle (ORC) and an absorption refrigeration system. Energy and exergy analyses were applied to the system and the effect of some key parameters were analyzed.

Although D-CAES technology has been optimized comprehensively, the dependence on fossil fuels and greenhouse gas emission are still its major disadvantages [20]. Therefore, the concepts of A-CAES were put forward to make CAES be fuels free [21]. In the A-CAES system, thermal energy generated during compression process is stored and then used to reheat air during expansion process [22–24]. Wolf [25] introduced a low-temperature CAES plant with the advantages of fast start-up characteristics and wide-ranging part load ability. In order to meet the end users' different need, some novel A-CAES systems allowing trigeneration of electrical, heating and cooling power in energy release process were presented in [26–28]. The results in [28] showed a 3% exergy efficiency increment and a lower round trip efficiency were obtained compared to the conventional A-CAES system. Wang [29] proposed a multi-level underwater A-CAES concept to improve performance over traditional systems challenged by fluctuating storage loads and user demands. Guo [30] adopted an ejector instead of a valve to regulate the compressed air pressure and the energy conversion efficiency was improved. In 2016, a pilot A-CAES plant was firstly reported by Wang [31]. Due to the low efficiency of compressor and thermal storage system, a low average round trip efficiency of 22.6% was achieved.

However, constrained by the efficiency and structure of compressor, the temperature of thermal energy stored should not be very high. Consequently, the electric power generated during energy release process in A-CAES will be difficult to enlarge and may not meet the requirements of large scale ESS. Also, the fossil fuels used to increase the gas temperature in D-CAES are not preferable for renewable energy conversion. Therefore, a novel hybrid wind-solar-compressed air energy storage (WS-CAES) system was proposed to overcome the disadvantages of both A-CAES and D-CAES in this paper. During the energy storage process, wind and solar power are stored in the forms of compressed air by compressor chain and thermal energy by solar thermal collector, respectively. Then during the energy release process, compressed